MODELLING STRUCTURAL FLEXURE EFFECTS IN CPV SUN TRACKERS

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ABSTRACT: Nowadays CPV trends mostly based in lens parqueted flat modules, enable the separate design of the sun tracker. To enable this possibility a set of specifications is to be prescribed for the tracker design team, which take into account fundamental requisites such as the maximum service loads both permanent and variable, the sun tracking accuracy and the tracker structural stiffness required to maintain the CPV array acceptance angle loss below a certain threshold. In its first part this paper outlines the author's approach to confront these issues. Next, a method is introduced to estimate the acceptance angle losses due to the tracker's structural flexure, which in last instance relies in the computation of the minimum enclosing circle of a set of points in the plane. This method is also useful to simulate the drifts in the tracker's pointing vector due to structural deformation as a function of the aperture orientation angle. Results of this method when applied to the design of a two axis CPV pedestal tracker are presented.

Keywords: Concentrators, Tracking

1. INTRODUCTION

The foreseen potential of high concentration photovoltaics is sought by almost all present players by means of module concepts which, resembling conventional flat plate PV panels, integrate a planar parquet of mini concentrator systems. This approach eases a rather separate design of the concentrator module on the one hand, and the sun tracker on which they will be mounted on the other, to the point they can be produced by different working groups. However in order to minimize the cost impact of the tracker on the CPV system, some parameters both in the module and the tracker must be rightly specified at onset and controlled during the design process. On the tracker's side the most important is the determination of its maximum service conditions, which specify the peak external loads, both permanent and variable, which must be withstood by the tracker structure always keeping its deformation below a certain threshold, which ensures that the acceptance angle loss of its CPV module array remains within certain set bounds. No matter how efficient the design, this specified stiffness will translate into tracker's weight, which when getting to volume productions represents its major cost driving factor. On the side of the module developers it is obvious that behind this overall acceptance angle loss control stands the module's nominal value from which this loss is subtracted, and optical designers must keep in mind that the wider the module's acceptance angle, the better for the tracker's cost. Bridging both development parties, the connection of the CPV modules atop of the tracker both from a mechanical point of view, where aperture planarity constitutes the main target, and from an electrical point of view where certain parallel-series interconnection schemes both within and among modules can prove more indulgent to structural deformations than others. In this process modeling structural flexure effects will aid in the *a priori* estimation of acceptance angle losses helping to better set the stiffness specifications, and can also be of use to enhance tracking accuracy in calibrated sun tracking control units such as Inspira's *SunDog® STCU.*

2. PERFORMANCE ISSUES IN A CPV TRACKER

Strictly speaking the main commitment to be fulfilled by a CPV sun tracker is to permanently align the pointing axis of the supported concentration system with the local sun vector, in this way producing maximum power output.

Reasons for the decrease of sun tracking performance can be classified into two main types, (i) those purely related to the precise pointing of the tracker to the sun and (ii) those which provoke shrinkage of the overall acceptance angle of the concentrator system thus indirectly increasing the tracking accuracy required. Among those related to the tracking accuracy these are basically on the one hand the exactness of the sun position coordinates generated by the control system expressed in terms of rotation angles of the tracking axes, either by sun ephemeris based computations or derived from the feedback of sun pointing sensor readings or a combination of both, and which in any case is affected by numerous error sources, and on the other the precision with which the tracker can be positioned at these dictated orientations, i.e. the positioning resolution of the tracking drive and its control system which essentially depends on the performance of tracking speed control and on the mechanical backlash introduced by the drive's gearings.

Regarding acceptance angle losses caused by the tracking system, these are due to the accuracy which can be attained in the mounting and alignment of the concentrator system atop of the tracker, which is basically in first instance a design problem having to do with the fixtures provided for this purpose, their accurate assembly and the regulation means provided for in-field fine tuning, but also with the mounting protocols devised to carry out this tasks. Also resulting in acceptance angle cuts is the stiffness conferred to the tracker, which is to say the deformations allowed in the different elements of its structure under service conditions.

3. MAXIMUM SERVICE CONDITIONS

Characterization of service conditions for a CPV tracker basically consists in determining the CPV array weight and fixing the maximum wind load i.e. wind speed, to be withstood during sun tracking operation with no effect in the concentrator's power output. To ensure service under these maximum permanent and variable loads a maximum flexure induced deformation is to be allowed for the tracker structure.

On the side of the variable loads, the bigger the maximum wind speed to be resisted maintaining productive operation, the heavier and more expensive tracking structure required to maintain deformations under the threshold required for accurate tracking.. A cost effective approach here is to determine this value from the cross correlation between wind speed and direct radiation, in the location or set of locations in which the trackers are planned to be marketed and installed. Above this point stiffness specifications do not have to be met, service is not guaranteed, and the tracker will better switch to some low wind profile stow position to decrease stress and increase operative lifetime. For example a 12m/s maximum wind load both windward or leeward to the modules in any of the sun tracking orientations of the tracker, can be considered a reasonably conservative value which has been proven to comprise a minimum of 95% of the direct radiation measured by the 26 weather stations of the SOLMET network distributed over the contiguous United States [1].

Regarding the CPV array payload, and again having in mind the targets to be placed on an eventual CPV module design group in order to decrease tracker cost, it will be a worthwhile effort to try and decrease the module's weight as much as possible.

In view of the said performance issues determining the maximum deformation allowed by the tracker structure which will not affect power output, basically depends on the achievable tracking accuracy and the modules' acceptance angle. The higher the tracking accuracy and the wider the nominal acceptance angle of a module, the bigger the deformation tolerance which can be set for the structure, and consequently the lower its cost.

For example say your modules have ±0.5° acceptance angle, here measured under the real sun (a ±0,26° extended source) and being the off track angle at which module's power output decreases down to 95% of the max power output. If the tracking control and drive can maintain a tracking accuracy always better than 0.1°, then there is a margin of 0.4° for an overall system acceptance angle loss due to on the one hand a certain degree of misalignment in the mounting of modules on the aperture and on the other due to flexure induced deformations. The errors in module alignment are a matter of regulation means and assembly protocols but will also be affected by underlying structural misalignments and lack of aperture planarity due to design weaknesses or manufacturing mistakes. Say we allocate 0.2° for each of the two acceptance angle loss sources, it is still to be determined how much structural deformation will result in this 0.2° and how this deformation is to be characterized.

4. ULTIMATE LIMIT STATE

Aside from the structural specifications derived from service conditions, basically determining the tracker's stiffness, its ultimate limit state and the loads at which this is reached is to be considered. This is usually a better paved way in the sense that there is a good set of international standard building codes, which even if not yet considering the particular case of sun trackers, the designer will be able to interpret and adapt them, dimensioning structural ultimate resistance for the recommended values of variable loads: wind and depending on the location snow and earthquakes. Along with these static loads, dynamic effects are also to be taken into account in what respects the resonant frequencies of the structure.

For a flat plate tracker, acceptance angle is meaningless and this ultimate limit state dimensioning constitutes its only structural specification; stiffness is here only an issue whenever an excess bending can somehow stress or damage the PV modules. However in the case of CPV trackers it can easily happen that the stiffness specifications are more stringent than the ultimate resistance ones, and that the fulfilment of the former implies that the latter are overridden. For this reason a CPV tracker, whichever its tracking axes configuration frequently results heavier than its conventional flat plate counterpart, and therefore somewhat more expensive, but on the other hand thanks to the fact that coming HCPV modules could even double the conventional PV efficiency, tracker cost per unit Wp is lower than in the flat plate case.

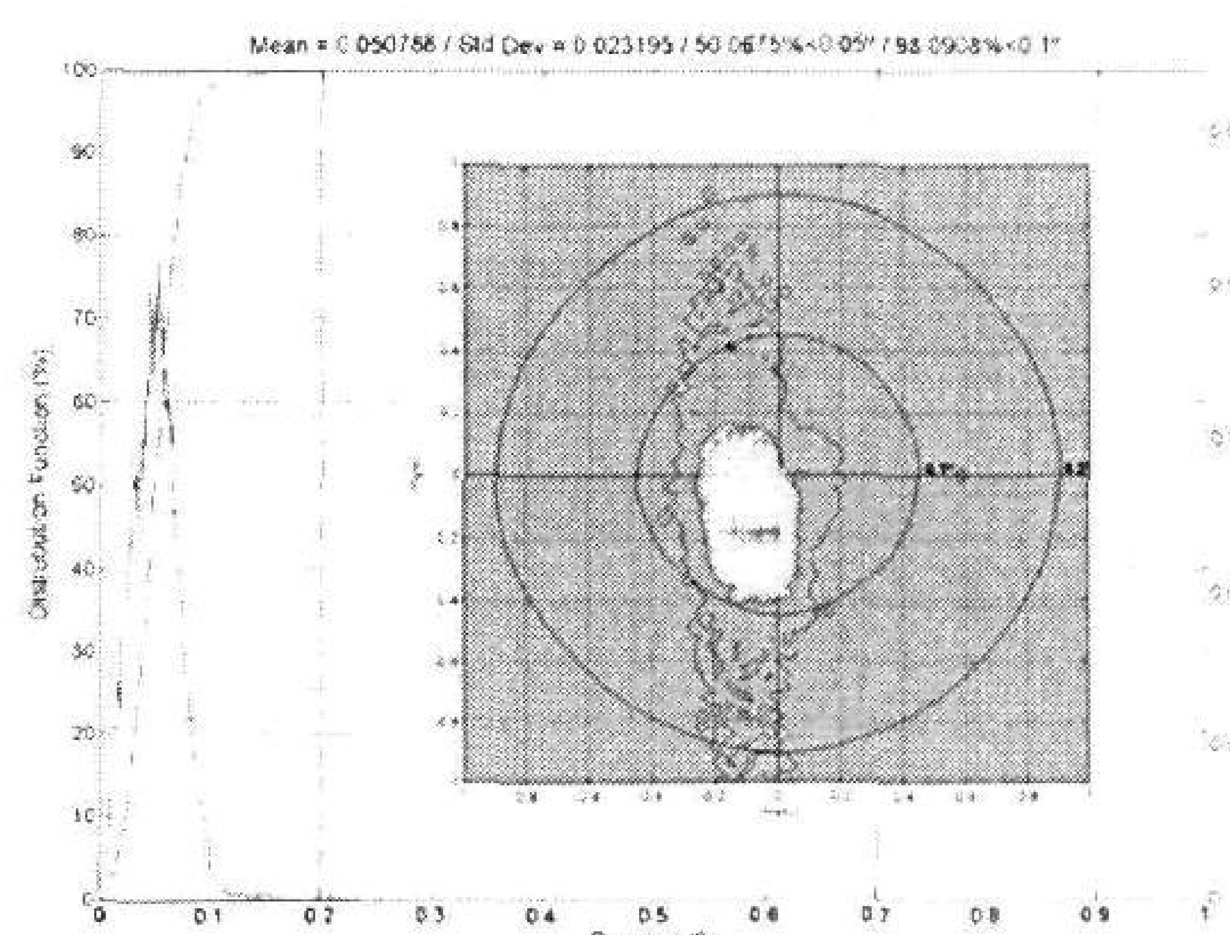

Figure 1: Tracking accuracy probability density and distribution function derived from the daily monitoring of a *SunSpear* tracking accuracy sensor installed on tracker controlled by the *SunDog STCU*. The collimated sunspot probability density over the SunSpear image sensor, encircled by the 0.1° and 0.2° rings, is inserted on the right.

5. SUN TRACKING ACCURACY

As seen a good tracking accuracy is a critical factor in order to bring down stiffness specifications and decrease tracker cost. There are several approaches to sun tracking control [2] going from the closed loop ones relying on sun pointing sensors to the open loop based on sun ephemeris computation, with a range of hybrid solutions in between. Inspira has developed the *SunDog* sun tracking control unit [3] which after an automatic calibration session based on closed loop accurate sun positioning by means of power output feedback, provides the necessary corrections to its sun ephemeris computation core, as characterised by a proprietary error model. From then on it operates as an open loop controller and in this way it has proven long term accuracies below 0.1° with 97% probability and below *0.05° with 60% probability. This has been measured* with Inspira's *SunSpear* tracking accuracy sensor based in solid state image sensors [4] (see Fig. 1).

6. ACCEPTANCE ANGLE LOSS ESTIMATION

We will here present a procedure to obtain acceptance angle loss, with respect to the nominal value of a single module, when an array of these is mounted atop of a tracker.

The estimate presented corresponds to that of a two axis pedestal tracker design, with a 30m^2 carried out by Inspira, which was customized for very high concentration ratio modules. In a first round maximum service conditions were set to 680kg of module payload and 12m/s maximum wind load both windward and leeward to the modules. A rather conservative 0.1° maximum bending under maximum service conditions was set as starting point for the tracking structure design. This means that this 0.1° is to be the maximum allowed turn induced by structural flexure for any vector normal to the aperture surface.

First in the design of the metal structure forming the tracker's aperture was deciding its topology, where only the lengths of dimensionless metal beams and the connections among them and with the drive block are decided, seeking here the optimization of different aspects such as transportation, in field installation, mounting of CPV modules etc but also its capacity to withstand the imposed flexure with the least weight.

Once the tracker frame is settled this is to be dimensioned playing with the precise form of the structural beams e.g. I-beams, angles and channels, or tubes if directly opting for off-the-shelf construction standards or others requiring more processing such as trusses, and assessing their moments of inertia and manufacturing costs.

6.1 Flexure simulation

It is beyond this point that the stiffness criterion starts to rule over the design, and precise Finite Elements (FE) analysis are to be carried out over the complete tracker structure when subject to the specified maximum service loads (CPV modules payload and maximum operative wind loads). When this was done for the referred tracker, a solution based on standard structural beams was obtained, which resulted in the least tracker's self weight, and according to FE simulations did not surpass the 0.1° bending at any aperture elevation. In the case of the pedestal tracker the design was separately considered in three segments, (i) aperture frame (ii) pedestal and drive block and (iii) foundation. From a start a certain percentage of that total maximum 0.1° maximum flexure was allocated to each segment, taking into account that while bending in the aperture will usually result in overall acceptance angle shrinkage, bending in the pedestal or the foundation works as an overall pointing vector turn which can eventually be characterized and handled by a tracking controller such as *SunDog*. In the case of the tracker's foundation, meeting its flexure quota requires a standard geotechnical analysis of the ground where it will be installed, in order to choose the best suitable solution. Quite obviously in a pedestal tracker with a rectangular aperture surface, maximum bending at whichever elevation will occur in its corners. Final *results for this design can be seen in figure 2,* where maximum bending when maximum service wind load comes frontally is 0.076° and occurs at 57° aperture elevation, while when this same wind speed is received in the aperture's rear face this maximum bending is *slightly bigger, 0.078° and happens at 0° elevation. In any* case maximum structural bending remains under the 0.1° threshold

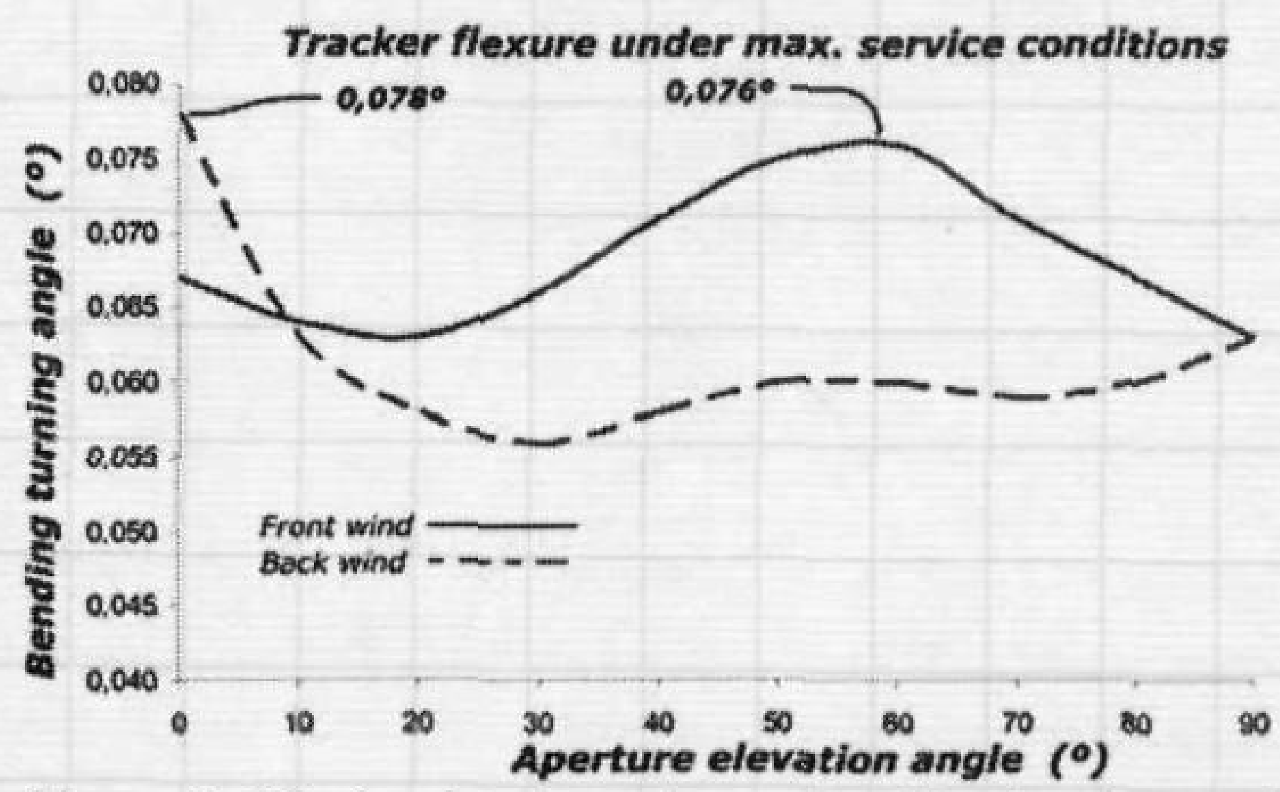

Figure 2: FE simulated maximum bending turning angle at every elevation under maximum service conditions for the 30m^2 aperture pedestal tracker.

6.2. Acceptance angle loss estimation

Once this maximum bending threshold has been met, next step is to estimate the acceptance angle losses induced by structural flexure, using the bending rotation values of the set of vectors normal to the aperture, obtained in the FE simulation. For this purpose a first geometrical model was developed in which assuming each CPV module mounted on the aperture could be considered to remain undeformed under service loads, a single normal vector is considered per CPV module. This normal vector is taken as the pointing vector of the module, i.e. that vector that when aligned with the local sun vector produces the module's maximum power output. Acceptance angle for each module is characterized by the cone drawn by the vectors at this angle from the pointing vector which is then the cone's axis. Simplifying, power is assumed to drop down to zero outside the acceptance angle cone, and a worst case approach is taken regarding the module's electrical interconnection, in which all modules are supposed to be connected in series. Thus the set of tracker orientations producing nominal power output for a certain aperture elevation angle is taken as the set of vectors pertaining to the acceptance angle cones of all the modules, i.e. their intersection. The acceptance angle at this aperture elevation can then be defined as the maximum angle cone contained in this intersection of cones, and the axis of this cone is taken as the overall concentrator pointing vector.

The problem of determining this overall acceptance angle cone can be better viewed and solved, if the pointing vectors and their respective acceptance angle cones are projected in the plane, using the usual PQ plane projection of non-imaging optics. This means that it is the projection of the intersection of pointing vectors and cones with a unit radius sphere whose center coincides with the origin of all the pointing vectors. In this way every module pointing vector is transformed into a point in the plane, having as Cartesian coordinates its direction cosines with respect to the plane reference axes and cones are transformed into ellipses. The flexure turning angle of a certain pointing vector will be small and therefore its projected coordinates appear very close to the reference system origin, which represents the pointing vector of the concentrator if the tracker was ideally rigid, and the distance of each pointing vector to the origin is its bending rotation angle. For these pointing vectors points located close to the origin its corresponding acceptance angle ellipse can be approximated by a circle, centered in the pointing vector coordinates. On the other hand high concentration CPV modules usually have small acceptance angles in the sub-degree range, and in this case the radius of the projected circle representing the acceptance angle cone equals the acceptance angle itself. So after this projection we can reformulate the problem of obtaining the maximum cone contained in the intersection of module acceptance angle cones, as the maximum incircle to the intersection of acceptance angle circles in the plane, and the center of this incircle — the incenter — represents the projection of the overall concentrator pointing vector. It can be proven that finding this maximum incircle is equivalent to determining the minimum enclosing circle (MEC) containing all the pointing vector points, where the center of this MEC coincides with the incenter of the maximum incircle and the radius of the maximum incircle, i.e. the overall acceptance angle, equals the single module acceptance angle minus the radius of the obtained MEC which in this way represents the acceptance angle loss due to flexure. MEC determination for a set of points in the plane is a classical computational geometry problem first stated by Sylvester in 1857 and for whose solution we implemented the most efficient algorithm to date due to Welzl and achieving *O(n)* linear running time [5].

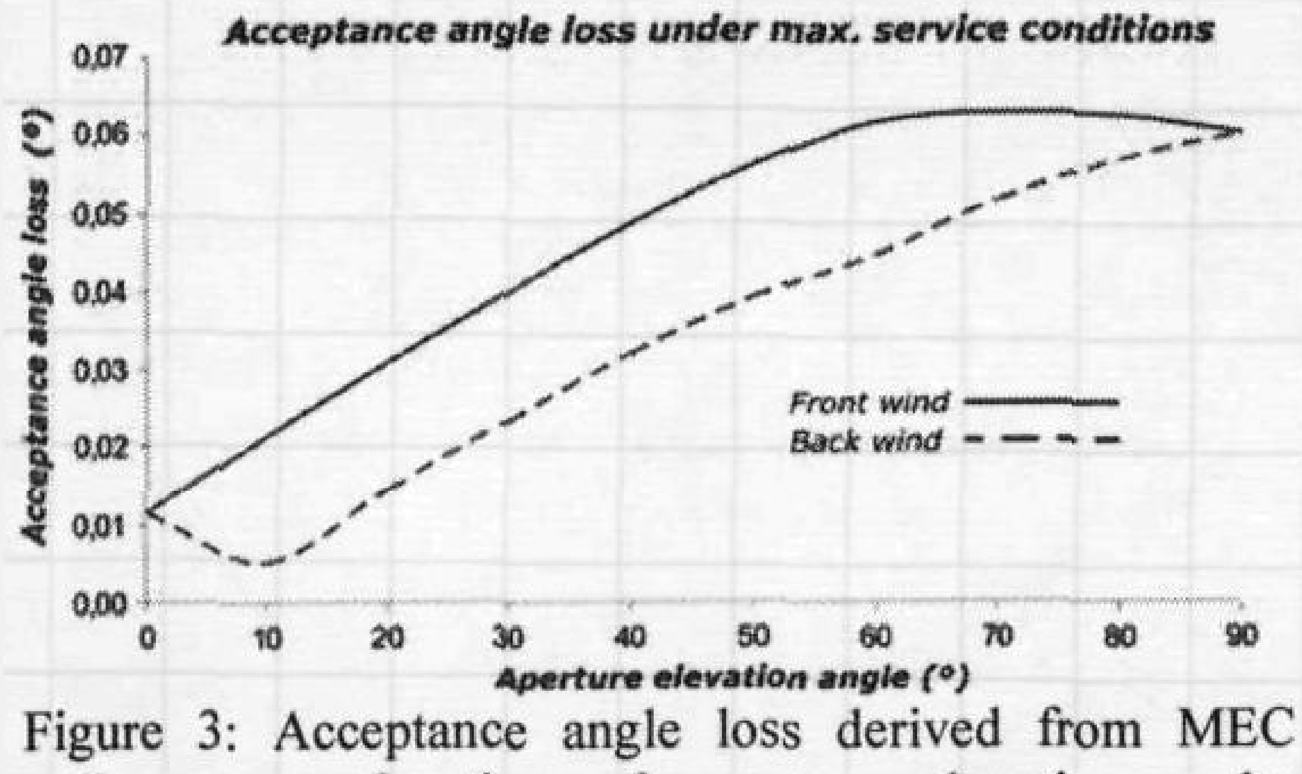

Figure 3: Acceptance angle loss derived from MEC radius as a function of aperture elevation under maximum service conditions both windward and leeward to the modules.

Applying this model to the FE simulations obtained from the pedestal tracker of our case example, produced the plot of acceptance angle loss as a function of aperture elevation for both front and back maximum service wind speeds shown in figure 3. The maximum loss is 0.063° and occurs with maximum service wind blowing windward to the modules at 70° of aperture elevation. So our initial 0.1° maximum bending threshold, finally achieving 0.078°, has finally resulted in a maximum acceptance angle loss of 0.063. Aperture elevation angle producing maximum bending of local pointing vectors and maximum acceptance angle loss do not necessarily coincide because as said in this analysis the turning angle considered is also affected by the pedestal and global components which equally affect all aperture pointing vectors and do not contribute to acceptance angle losses. So again reviewing the starting figures regarding module nominal acceptance angle and feasible accuracy attainable would give way to further relax the bending threshold in a second iteration, thus further lightening the structure and reducing its cost.

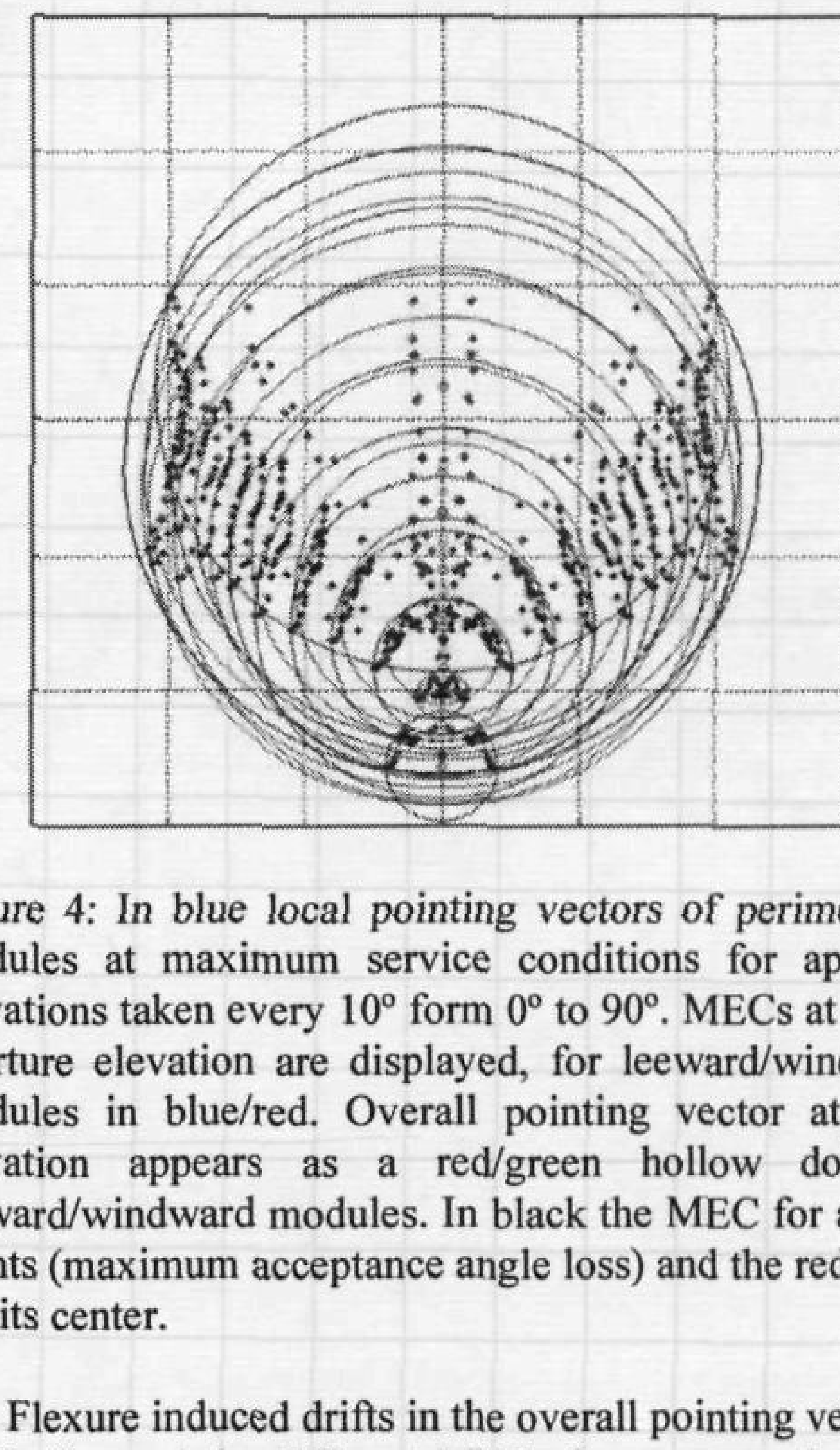

Figure 4: In blue local pointing vectors of perimetrical modules at maximum service conditions for aperture elevations taken every 10° form 0° to 90°. MECs at every aperture elevation are displayed, for leeward/windward modules in blue/red. Overall pointing vector at each elevation appears as a red/green hollow dot for leeward/windward modules. In black the MEC for all the points (maximum acceptance angle loss) and the red solid dot its center.

6.3. Flexure induced drifts in the overall pointing vector

In figure 4 the different MECs for aperture elevation angles taken every 10° from 0° to 90° are shown along with the centers of each MEC, which shows how the overall pointing vector also moves due to flexure. The local pointing vectors used at every elevation for MEC determination are only those of the modules placed in the aperture perimeter, which are the ones suffering the biggest bending.

Figure 5 plots how the pointing vector rotates around the elevation axis under maximum service loads as a function of the elevation showing an excursion of ±0.04°.This behaviour can be described by means of a suitable interpolation function and integrated in the calibration model of a hybrid sun tracking control unit such as Inspira's *SunDog* STCU. In this way tracking accuracy is enhanced, thus allowing some extra acceptance angle loss. However with regards to tracking accuracy this pointing vector drift is to be modelled considering wind load as a random noise and calibrating on a calm day.

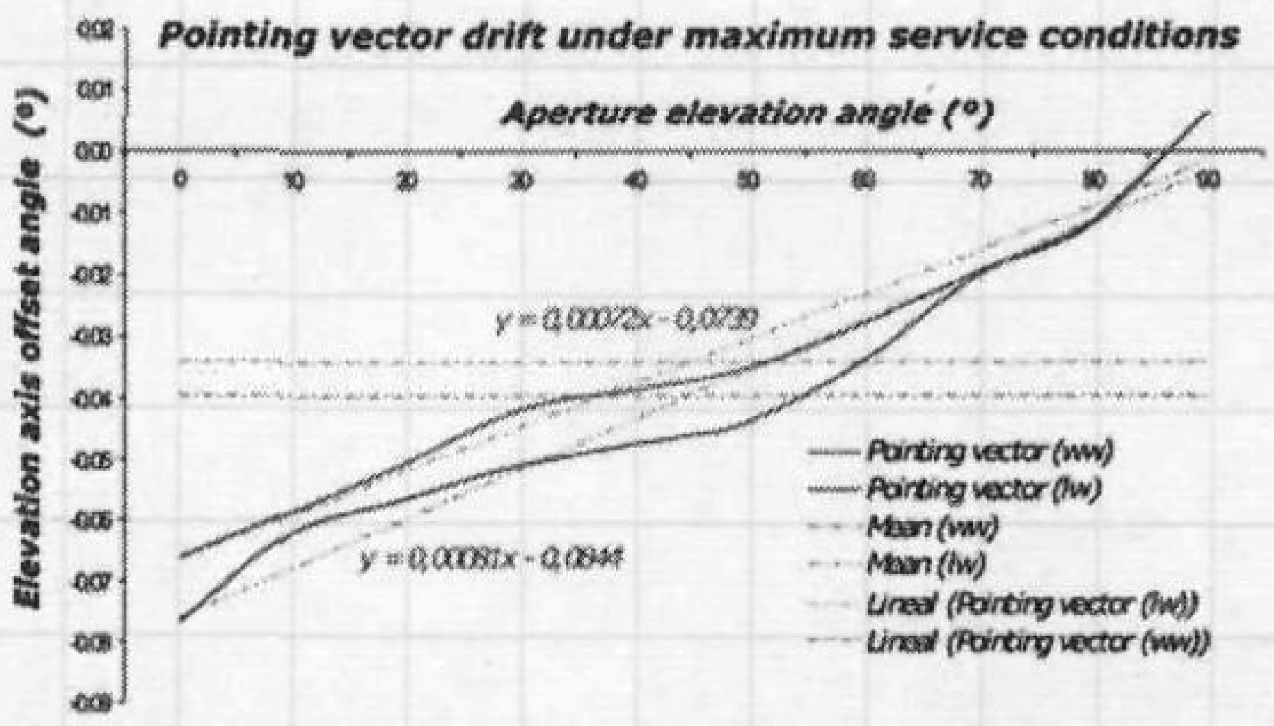

Figure 5: Overall pointing vector position drift due to its flexure induced turning around the elevation axis as a function of aperture elevation under maximum service conditions both windward and leeward to the modules

7. CONCLUSION

This paper attempts to characterise the main factors determining the design of a CPV tracker. Tracking accuracy is basically a mater of a precise determination of the sun local coordinates and the subsequent accurate positioning of the tracker on these. This tracking accuracy is to be within the acceptance angle of the CPV *system. In a modular* CPV *array, the overall acceptance* angle of the system suffers losses with respect to the module's nominal value, mainly due to the lack of planarity in module assembly and to the deformations suffered by the tracking structure under service conditions. Certain stiffness is to be specified for the tracking structure in order to restrain acceptance angle losses. Structural stiffness translates into structural weight which is one of the tracker's major cost driving factors when entering into volume productions. The higher the tracking accuracy and the CPV module's nominal acceptance angle, the better in order to pull down a tracker's design cost. To aid in the estimation of the acceptance angle loss due to structural deformations a geometrical model is presented based in the determination of the minimum enclosing circle which is also useful to simulate the drifts in the tracker's pointing vector and help in the assessing of calibration models which enhance tracking control accuracy.

8. REFERENCES

[1] I. Luque-Heredia *et al.* " A Subdegree Precision Sun Tracker for 1000X Microconcentrator Modules" Proceedings 3rd World Conference on Photovoltaic Energy Conversion, Osaka, Vol. A (2003) 857-860

[2] I. Luque-Heredia, J.M. Moreno, G. Quéméré, R. Cervantes, P.H. Magalhães "CPV Sun Tracking at Inspira" Proceedings 3rd International Conference on Solar Electric Concentrators, Scottsdale, (2005)

[3] I. Luque-Heredia, J.M. Moreno, G. Quéméré, R. Cervantes, P.H. Magalhães "SunDog STCU: A Generic Sun Tracking Control Unit for Concentration Technologies" 20th European Photovoltaic Solar Energy Conference, Barcelona, (2005) 2047-2050

[4] I. Luque-Heredia, R. Cervantes, G. Quéméré. "A Sun Tracking Error Monitor for Photovoltaic Concentrators" Proceeding 21st. European Photovoltaic Solar Energy Conference, Dresden (2006) to be published.

[5] E. Welzl. "Smallest Enclosing Disks (Balls and Ellipsoids)" Lecture Notes in Computer Science, 555, (1991) 393-370.